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Motion compensated inverse filtering with bandpass filters for LCD motion blur reduction

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## Motion Compensated Inverse Filtering with Bandpass filters for LCD Motion Blur Reduction

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### ABSTRACT

New displays, such as Liquid Crystal Displays (LCDs), typically emit light during the whole frame time. In contrast, traditional Cathode Ray Tubes (CRTs) emit light as very short pulses, which gives the CRT a better dynamic resolution. As a consequence, LCDs suffer from motion artifacts, which are visible as a blurring of moving objects. 'Motion Compensated Inverse Filtering', uses motion vectors to apply a pre-correction to the video data, and recovers the sharpness of moving images to a large extent. Noise amplification due to the high gains in the ideal inverse filter is a drawback of this method. In this paper we propose to change the filter response as a function of speed, such that at higher speeds, high spatial frequencies are not amplified. This is contrary to the inverse filtering theory, but increases noise robustness while maintaining the motion blur reduction effect.

**Keywords:** Video processing, Liquid Crystal Displays, LCDs, motion blur

### 1. INTRODUCTION

Over the last years, the traditional cathode ray tube (CRT) display has had to face increasing competition from alternative display principles, which are mainly based on active-matrix technology. In particular, active-matrix liquid crystal displays (AM-LCDs) have increased in performance and decreased in price so dramatically, that the market share of the CRT is decreasing at a rapid pace. The main differentiating feature of these new display principles is their size: LCDs are thin, flat and lightweight. This has enabled the first market for these displays: laptop computers. By now, the LCD has also almost taken over the desktop monitor market, where not only its size has made the difference, but also its uniform, sharp, and flicker-free picture reproduction. Nowadays, the CRT is also having to face competition from the LCD in its last stronghold: television.

To make a good television display, the LCD has had to overcome previous drawbacks, for example a limited viewing angle and color performance. However, the CRT is still unbeaten in one major aspect: motion portrayal. In that area, LCDs perform much worse, since the LC-molecules that provide the basic display effect react slowly to image changes. This causes an annoying smearing (blurring) of moving objects, which makes the LCD unsuited for video applications. Therefore, a lot of effort has been put into speeding up the response of LC materials. This can be done by applying better materials, or by improved LC cell design. There is also a well known method for response time improvement based on video processing, called 'overdrive'.<sup>1</sup> Overdrive improves the response speed of the LC pixels by changing the drive values depending on the applied gray level transition. This enables a reduction of the response time to within the frame period. Currently, the best displays available list response times below the frame period (17ms at 60Hz). This is a crucial value, since the worst blurring artifacts are prevented for an LCD that can respond to image changes within the frame period.

However, speeding up the response of LC materials to lower values is not enough to completely avoid motion blur.<sup>2,3</sup> This is caused by the active matrix principle itself, which exhibits a sample-and-hold characteristic, causing light emission during the whole frame time. This is a major difference with the very short (microsecond) light flashes produced by the phosphors of the CRT. It is well known<sup>2,3</sup> that this prolonged light emission does not match very well with the way humans perceive moving images. As will be further explained in the next sections, the human eye will track moving objects on the screen, thereby imaging the light, belonging to each fixed point in a frame, onto a series of points on the retina. This 'point spreading' results in a loss of sharpness of moving objects.

A number of measures have been proposed<sup>2</sup> to reduce this effect, mostly by modification of the display. In this paper, we describe a method called 'motion compensated inverse filtering' that can reduce motion blur on LCDs by means of video processing prior to the display. The possibility of such a 'pre-compensation' method

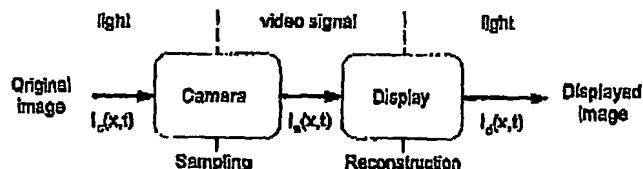


Figure 1. Basic display chain: original image - sampled image - displayed image.

has previously been reported,<sup>4-6</sup> and in this paper we describe the implementation based on a frequency domain analysis of the motion blur effect. The paper is structured as follows: Section 2 describes the analysis, Section 3 describes the basic algorithm, Section 4 describes the proposed improvement, and finally results are presented and conclusions are drawn in Sections 5 and 6.

## 2. ANALYSIS OF THE MOTION BLUR EFFECT

The basic function of a display system is to reconstruct the physical light emissions, corresponding to the original image, at the correct position and time on the screen from the received space-time discrete video signal. The characteristics of this reconstruction process, especially when combined with characteristics of the human visual system, can explain many image quality artifacts that occur in practical display systems. In order to find a pre-compensation for the blurring artifact of the display, we analyse the displayed image in the frequency domain.

The very basic representation of the signal chain from source to displayed image is shown in Figure 1. The original scene, represented as a time varying image, is a space-time-continuous intensity function  $I_c(\vec{x}, t)$ , where  $\vec{x}$  has two dimensions:  $\vec{x} = (x, y)^T$ . This original image is sampled (by the camera) in time and space. Since the spatial sampling is outside the scope of this paper, we will refer to it only occasionally from now on. The temporal behavior, however, will be the main focus for the remainder of this paper.

The sampling process is described by:

$$I_s(\vec{x}, t) = I_c(\vec{x}, t) \cdot A(\vec{x}, t), \quad (1)$$

where  $A(\vec{z}, t)$  is a three-dimensional lattice of  $\delta$ -impulses.<sup>7</sup> We can assume a rectangular sampling lattice, which is described by sampling intervals  $\Delta \vec{z} = (\Delta x, \Delta y)$  and  $\Delta t$ :

$$\delta(\vec{x}, t) = \sum_{k,l,m} \delta(x - k\Delta x) \delta(y - l\Delta y) \delta(t - m\Delta t) \quad (2)$$

The reconstruction of the physical light emission by the display can be described by a convolution with the display aperture (also known as reconstruction function or point spread function). This aperture is also a function of space and time:  $A(\vec{x}, t)$ . The image, as produced by the display, becomes:

$$J_a(\vec{x}, t) = J_s(\vec{x}, t) + A(\vec{x}, t) \\ = (J_a(\vec{x}, t) \cdot A(\vec{x}, t)) * A(\vec{x}, t) \quad (8)$$

The two operations of sampling and reconstruction account for a number of characteristic differences between the displayed image and the original. These are best described by a frequency domain description, so we apply the Fourier transform  $\mathcal{F}(F(\vec{x}, t)) = F^I(\vec{f}_x, f_t)$  to Eq. 3:

$$I_g^f(\vec{f}_x, f_t) = \left( I_g^f(\vec{f}_x, f_t) * A^f(\vec{f}_x, f_t) \right) \cdot A^f(\vec{f}_x, f_t), \quad (4)$$

where the Fourier transform  $A^F(f_x, f_y)$  of lattice  $A(\bar{x}, \bar{t})$  is the reciprocal lattice, with spacings  $(\Delta x)^{-1}$ ,  $(\Delta y)^{-1}$  and  $(\Delta t)^{-1}$  (the frame rate).

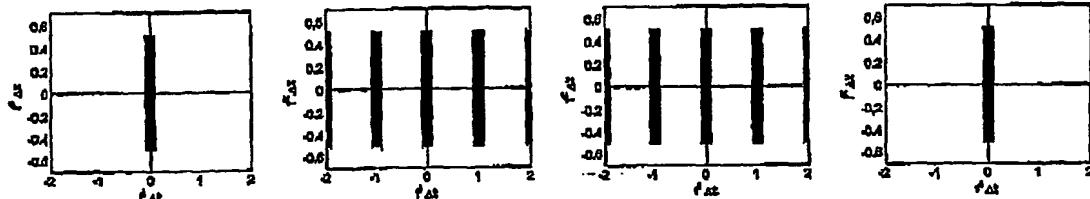


Figure 2. Basic display chain for an impulse-type display. Shown is the spatio-temporal frequency spectrum for, from left to right: original image  $I_o$  - sampled image  $I_s$  - displayed image  $I_d$  with impulse display - perceived image after eye low-pass  $I_p$ .

### 2.1. Impulse display types

The resulting spectrum of the displayed image is shown in Figure 2 for an impulse-type (CRT) display. To simplify the illustration, we omit the spatial repeats, as if the signal was continuous in the spatial dimension. For the displayed images, this is equivalent to assuming that the spatial dimension has been reconstructed perfectly, i.e. the original continuous signal was spatially band-limited according to the Nyquist criterion, and the reconstruction effectively eliminates the repeat spectra. In the temporal dimension, the impulse nature of the light emission gives a flat reconstruction spectrum. As a consequence of this flat spectrum, the temporal frequencies in the basoband ( $f_t < (2\Delta t)^{-1}$ ) are not attenuated, but also at least the lowest order repeats are passed.

The image, as it is finally perceived by the viewer, is also determined by the characteristics of the human visual system (HVS). In the temporal domain, the HVS mainly behaves as a low-pass filter, since it is insensitive to higher frequencies.<sup>8</sup> Figure 2 shows that the perceived image is identical to the original image, if we assume that the eye's low-pass eliminates all repeat spectra. This assumption is not always true, which leads to one of the most widely known artifacts in display systems: large area flicker. This is caused by the first repeat spectrum (at low spatial frequencies) that is not completely suppressed for frame rates  $\leq 75\text{Hz}$ .

### 2.2. Sample-and-hold display types

Active-matrix displays like LCDs do not have an impulse-type light emission. The fastest displays that are currently available have response times shorter than the frame period. However, even these will still have a light emission during the whole frame period due to the sample-and-hold behavior of the active matrix and the continuous illumination by the backlight. This behavior results in a temporal 'box' reconstruction function with a width equal to the hold time  $T_h$ . In the frequency domain, this becomes a sinc characteristic:

$$A^f(f_x, f_t) = \text{sinc}(\pi f_t T_h) \quad (5)$$

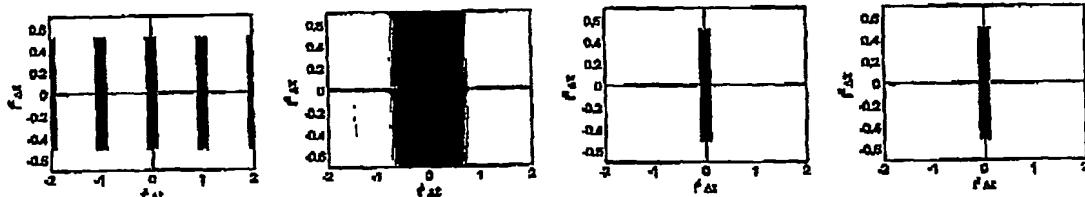


Figure 3. Basic display chain for a hold-type display. Shown is the spatio-temporal frequency spectrum for, from left to right: sampled image  $I_s$  - aperture function  $A$  (note: white=low, black=high) - displayed image  $I_d$  - perceived image after eye low-pass  $I_p$ .

The displayed image according to Eq. 3 is shown in Figure 3. This immediately shows a distinctive advantage of hold-type displays over impulse-type displays: the sinc characteristic suppresses the repeat spectra, and even has zero transmission at the sampling frequency. This eliminates large area flicker at all frame rates.

### 2.3. Displaying moving images

It may seem that the sample-and-hold behavior results in a better display than an impulse light emission. For static images this is indeed the case. However, the conclusion changes for a moving image:

$$I_m(\vec{x}, t) = I_c(\vec{x} + \vec{v}t, t), \quad (6)$$

where  $\vec{v}$  is the speed\* of the moving image over the screen. Eq. 6 can also be transformed to the frequency domain,<sup>7</sup> where it becomes:

$$I_m^f(\vec{f}_x, f_t) = I_c^f(\vec{f}_x, f_t - \vec{v} \cdot \vec{f}_x) \quad (7)$$

This results in a shearing of the spectrum as shown in Figure 4, reflecting that spatial variations in a moving object will generate temporal variations.<sup>7,9</sup>

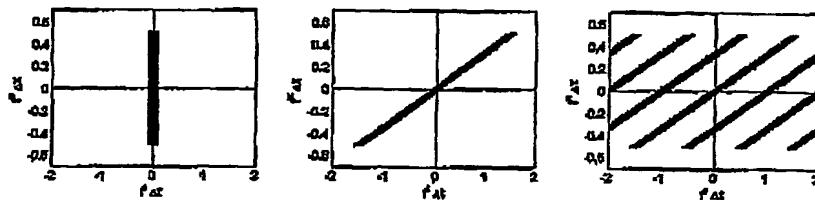


Figure 4. Moving image spectrum: original (still) image  $I_c$  - moving image  $I_m$  - sampled moving image  $I_s$ .

This moving image is then sampled and reconstructed in the display chain, after which it reaches the eye. The perception of moving images is characterized by another important property of the HVS: the eye tracking. The viewer tries to follow moving objects across the screen in order to produce a static image on the retina. This mechanism is well studied,<sup>10</sup> and enables the HVS to perceive moving images with a high level of detail.<sup>11</sup> The image on the retina of an eye tracking viewer is described by the inverse of the relations in Eqs. 6 and 7:

$$\begin{aligned} I_d(\vec{x}, t) &= I_s(\vec{x} - \vec{v}t, t) \\ I_d^f(\vec{f}_x, f_t) &= I_s^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x) \end{aligned} \quad (8)$$



Figure 5. Display chain: original (still) image - moving image - sampled image - displayed image - eye tracking - low-pass filtering.

The whole chain from original image to perceived image is shown in Figure 5. Substituting Eq. 3 in Eq. 8 and applying Eq. 7, gives the image as projected onto the retina of the eye tracking viewer:

$$\begin{aligned} I_c^f(\vec{f}_x, f_t) &= (I_m^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x) * A^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x)) \cdot A^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x) \\ &= (I_s^f(\vec{f}_x, f_t) * A^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x)) \cdot A^f(\vec{f}_x, f_t + \vec{v} \cdot \vec{f}_x) \end{aligned} \quad (9)$$

\*Here the speed is measured in the units used for  $\vec{x}$  and  $t$ . When the sampling intervals  $\Delta\vec{x} = (\Delta x, \Delta y)$  and  $\Delta t$  are known,  $\vec{v}$  can also be expressed in 'pixels per frame'. This corresponds to the 'motion vector' or 'frame displacement vector'.

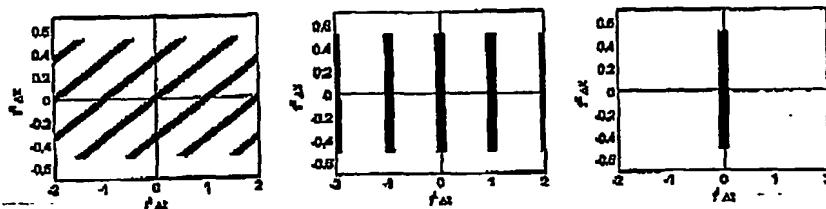


Figure 6. Perceived moving image on an impulse-type display. The first part of the chain is shown in Figure 4. The second part is shown here, from left to right: Displayed image  $I_d$  - after eye tracking  $I_e$  - after eye low-pass  $I_p$ .

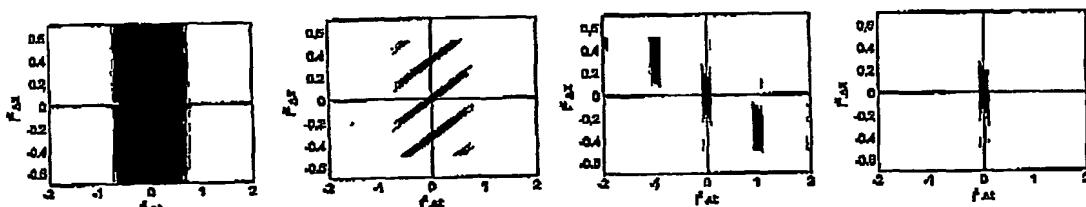


Figure 7. Perceived moving image on a hold-type display. The first part of the chain is shown in Figure 4. The second part is shown here, from left to right: Aperture function  $A$  - displayed image  $I_d$  - after eye tracking  $I_e$  - after eye low-pass  $I_p$ .

The perceived image  $I_p'(\vec{f}_x, \vec{f}_z)$  after low-pass filtering by the eye is shown in Figure 6 for an impulse-type display, and in Figure 7 for a hold-type display. The image after eye low-pass is obtained by only looking at the frequencies  $f_t \approx 0^\circ$ . There we can see that the effect of the temporal aperture function of the display, combined with eye tracking, can be described as spatial filtering of moving images:

$$\begin{aligned} I_p'(\vec{f}_x) &= I_d(\vec{f}_x) \cdot A^f(\vec{f}_x, \vec{f}_z) \\ &= I_e(\vec{f}_x) \cdot \text{ sinc}(\pi \vec{f}_x \cdot \vec{f}_z T_h) \end{aligned} \quad (10)$$

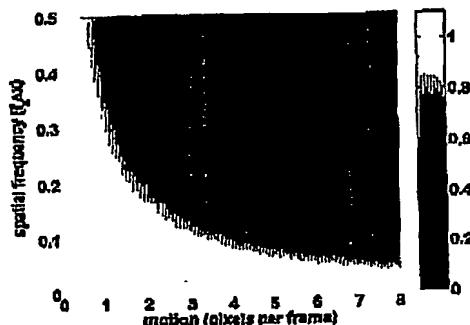


Figure 8. Amplitude response of the spatial filtering due to the temporal display aperture and eye tracking, as a function of spatial frequency and speed (in pixels per frame, if we express  $f_w$  in cycles per pixel, and  $T = 1$  frame).

<sup>†</sup>We again assume perfect reconstruction in the spatial domain

The filter of Eq. 10 depends on the speed of motion  $\vec{v}$  and the hold time (frame period)  $T_h$ . Figure 8 shows the amplitude response of this filter as a function of speed ( $|\vec{v}|$ ) and spatial frequency along the motion direction ( $\vec{f}_x \cdot \vec{v}/|\vec{v}|$ ). Although the temporal 'hold' aperture is beneficial with respect to large area flicker, it will cause a spatial blurring of moving objects on the retina of the viewer. Higher spatial frequencies will be attenuated by the sinc characteristic, and this attenuation will increase with speed. Furthermore, this blurring will only occur along the motion direction (see also Section 3). The sharpness perpendicular to the motion of each object is not affected.

Eq. 10 suggests that, in order to decrease this effect, the hold time  $T_h$  must be decreased. This can be achieved in two ways. First of all, the frame rate can be increased. In order to have the required effect, this must be done with a motion compensated frame rate conversion, since a simple frame repetition will result in the same effective hold time. Secondly, without changing the frame rate, we can decrease the period (or better: duty-cycle) of light emission. For LCDs, this can be realized by switching the backlight on only during a part of the frame time, using a so-called 'scanning backlight'.<sup>2</sup> In Section 3, we describe a third option for decreasing motion blur due to the sample-and-hold effect, based on Eq. 10. This method uses only video processing and does not require modification of display or backlight.

### 3. MOTION COMPENSATED INVERSE FILTERING

As an alternative to altering the properties of the display to overcome the sample-and-hold effect, we seek to decrease the effect by video processing.<sup>4</sup> This means that we will try to pre-compensate for the low pass filtering of the display+eye combination in the video domain, as shown in Figure 9. To this end, we define the 'inverse filter' to Eq. 10, of which the amplitude response is shown in Figure 10a:

$$H_{inv}^f(\vec{f}_x) = \frac{1}{\text{sinc}(\pi \vec{v} \cdot \vec{f}_x T_h)} \quad (11)$$

This is a purely spatial filter, reflecting the observation that the temporal aperture of the display, combined with eye tracking, results in a spatial low-pass filter. The cascade of the inverse filter and the display+eye combination further along the chain should result in a perceived image that approaches the original image as well as possible.

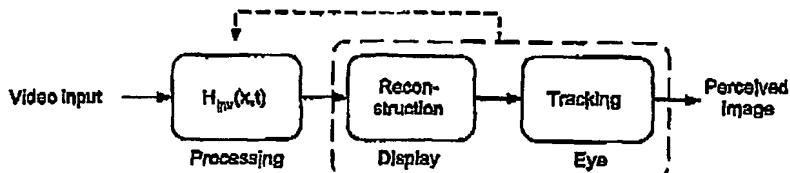


Figure 9. A pre-compensation (inverse) filter is applied to reduce the motion blur effect of the display+eye combination.

A similar problem is known from image restoration, where the blurring of images due to camera motion is considered.<sup>12</sup> The solution involves a 'deconvolution' of the signal with the blurring kernel (i.e. Eq. 11). This is however not a good solution for our problem, due to the following reasons. First of all, these methods are very computationally intensive. Secondly, objects in the image can have many different speeds, which requires a locally adaptive method. Therefore, we propose an alternative solution: 'Motion Compensated Inverse Filtering' (MCIF).

From the characteristics of the filter described by Eq. 11, a number of observations can be made. First of all, we already mentioned that the motion blur only occurs in the direction of the motion, i.e. only frequency components parallel to the motion direction are attenuated. The vector dot-product  $\vec{v} \cdot \vec{f}_x$  is zero for components  $\vec{f}_x$  perpendicular to  $\vec{v}$ , and the filter has no effect on these frequencies. Therefore, we can simplify the inherently two-dimensional behavior of the filter by only considering frequencies parallel to the motion. However, the inverse filter must act along the motion vector, which can be oriented in any direction. Therefore, a good motion

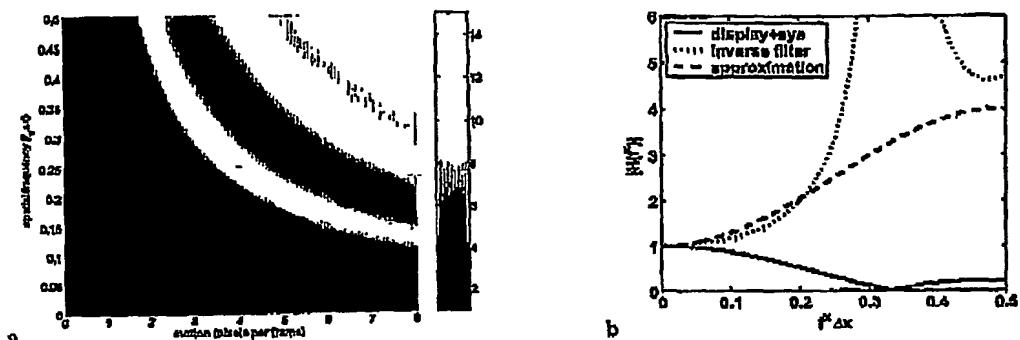


Figure 10. Amplitude response of a) the inverse filter as a function of speed, b) the display-eye filter ( $\text{sinc}$ ) for a speed of three pixels per frame, the corresponding inverse filter, and a simple approximation.

estimator is needed. We use a 3-D recursive search blockmatcher.<sup>13</sup> ICs based on this estimator have been available at a consumer price for some years.<sup>14</sup> This type of motion estimator has the very important property that it is able to estimate the true motion of objects. True motion vectors are essential for this application, as this is the motion that describes the eye tracking of the viewer for each separate object.

Furthermore, the  $\text{sinc}$  characteristic may contain zeros, which will lead to an infinite gain in the inverse filter. The frequencies that correspond to these zeros depend on the motion speed and cannot be compensated. Therefore, we can only hope to approximate the original, as the inverse filter can never be perfect. Figure 10b shows the frequency response (parallel to the motion) of the display-eye combination and of the inverse filter, for a speed of three pixels per frame.

Also plotted in Figure 10b is the response of a very simple three tap  $[-1, 2, -1]/4$  high-pass filter added to the original. When the gain of this filter is adjusted, the inverse filter can be approximated to a reasonable extent for different speeds. The resulting compensation system then becomes very simple, as shown in Figure 11.

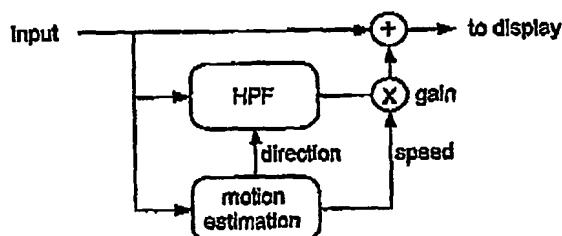


Figure 11. Motion compensated inverse filtering. The high-pass filter (HPF) is oriented along the direction of the motion, and the gain is controlled by the speed of the motion

This is the basic implementation of MCIF, which can also be seen as a motion-dependent sharpness enhancement ('peaking') filter. The main difference with existing sharpness enhancement is the fact that it also depends on motion information and that the response is tuned to the motion blur property of the display. The MC-inverse filter is oriented along the motion vector by rotating the 1-D kernel, which makes it essentially a 2-D filter. Figure 12 shows how the three taps of the high-pass filter are rotated according to the motion vector. Since the rotated-taps generally do not co-incide with sample positions in the image, we use an interpolation, e.g. bi-linear, to re-distribute the taps over image samples. Alternatively, we can interpolate the image samples to the tap positions, which results in a rotated line of samples that is multiplied with the filter tap coefficients.

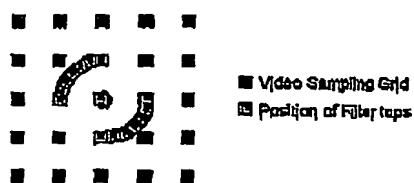


Figure 12. Motion direction dependent filtering.

Furthermore, the filter is adapted to the speed by varying the gain. Figure 13 shows the amplitude response of this filter, and the combined result of filter and display+eye (see Figure 9).

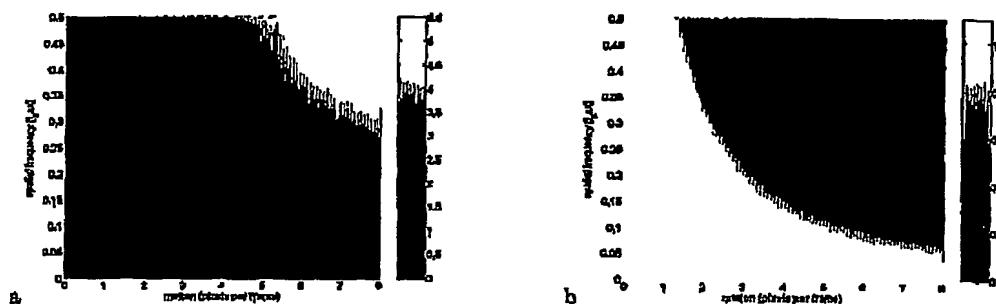


Figure 13. a) Amplitude response of a simple MCIF filter, along the motion direction. b) Combined response of MCIF and display+eye. Compare with Figure 8.

This implementation is indeed very simple, since the filter only uses three taps, which limits the vertical footprint (in case of a vertical motion) to three lines. The filter has been applied to real video sequences, which were displayed on a fast LCD panel (see also Section 5). Sharpness of moving images was considerably improved, but the simple implementation shows some limitations. These are caused by the fact that the filter gain becomes very high (larger than a linear factor of 5) already for moderate speeds. This results in two problems: dynamic range limitations and noise amplification. The dynamic range limitation is fundamental: we cannot compensate a black-to-white transition with any video processing method. However, in typical video source material, most transitions will be between intermediate gray levels, and so there is still room for improvement of these, as long as we maintain a limited gain.

### 3.1. Noise suppression

The amplification of noise is also problematic. We can argue that the viewer will follow the motion and therefore also perceives the high frequencies of the noise as being attenuated. Nevertheless, the images that result from the filter in Figure 11 show strongly amplified noise. Particularly in flat (undetailed) image parts, the motion estimator has a high chance of estimating the wrong vector, which can cause undesirable noise amplification at high MCIF gains. Therefore, we add a noise suppression to the system, as shown in Figure 14. The noise is suppressed by discarding the low-amplitude high frequencies, commonly called 'coring',<sup>9</sup> and by a non-linear order-statistical filter.<sup>15,16</sup> This will only apply the compensation in regions where there is sufficient signal, as these are also the regions where motion blur is most objectionable.

#### 4. SPEED DEPENDENT BAND-PASS FILTERING

As a further measure to reduce noise amplification, we observe that the display+eye filter (Figure 8) at high speeds has a considerable attenuation at already very low spatial frequencies. Furthermore, it is known that the human visual system is more sensitive to the lower spatial frequencies, and the higher frequencies generally have a lower signal-to-noise ratio. Nevertheless, the basic MCIF system will apply the highest gain to the highest spatial frequencies. Furthermore, in common video material, moving objects will not contain the highest frequencies due to the limitations of the camera (camera blur). For this reason, viewers are used to losing some detail at high speed, although not to the extent (up to lower spatial frequencies) that is caused by LCD panels.

Therefore, for higher speeds, we will give priority to compensation of the lowest affected frequencies, and leave the highest frequencies unchanged. This transforms the earlier introduced high-pass filter (Figure 11) into a band-pass filter. After combining (adding) the filtered signal to the input, the final MCIF result is a medium-frequency boosting filter. Note that this is in contrast to the theory in the previous sections.

In order to limit the amplification of the higher frequencies at high speeds, and only compensate the lowest frequencies. We extend the speed dependency of the MC-inverse filter from a simple varying gain and rotating but fixed response filter, to a varying filter response. To achieve this, we change the directional dependent interpolation. Figure 15 shows the implementation.

The interpolation uses a 2D neighborhood around the current pixel, and returns a 1D series (line) of samples to the filter. The samples resulting from the interpolation correspond to the taps of the filter. These samples are subsequently multiplied with the filter tap coefficients and accumulated, to result in a single 'correction' value for the current pixel. This operation is not a conventional convolution filtering, since the applied line of samples can totally change from one pixel to the next, if the motion vector changes.

The positions of these 'interpolated' taps vary not only with the direction of the motion vector, as in Figure 12 but also lie at a larger distance from the central tap for higher speeds. This shifts the response of the (still static) 1D high-pass filter to lower frequencies. Figure 16 shows the distribution of filter taps, and Figure 17 shows the 1D response as a function of speed of the rotated filter, and of the ideal inverse filter. Note that the gain of the filter is no longer changed (substantially) with speed. Figure 18 shows which samples on the input video grid are used to calculate each interpolated sample (for a bi-linear interpolation).

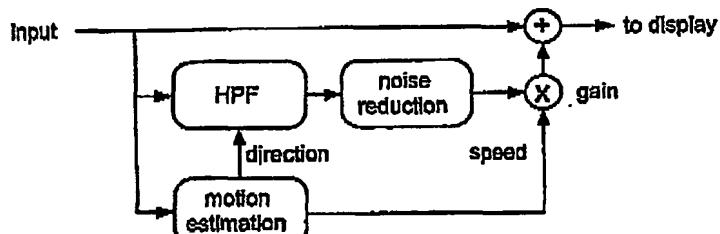


Figure 14. Motion compensated inverse filtering, with noise suppression.

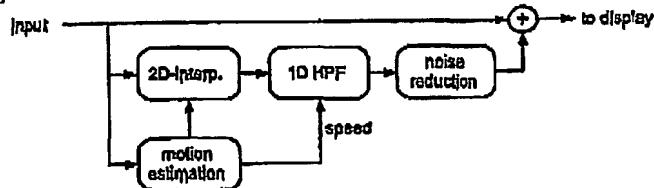


Figure 15. Motion compensated inverse filtering, with speed dependent filter.



Figure 16. Motion direction and speed dependant filter.

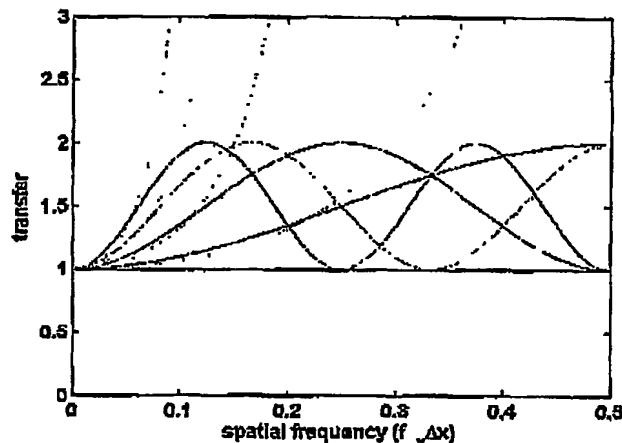


Figure 17. Response of filter with varying tap-distance, and the corresponding 'ideal' inverse filter for different speeds.

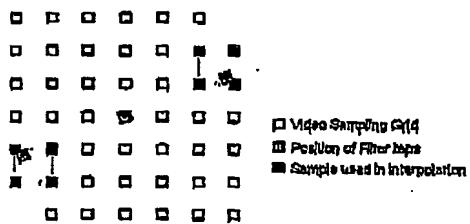


Figure 18. Samples used to interpolate the rotated filter

When the filter taps are simply shifted away from the central tap at increasing speed, high frequencies can still pass the filter. This happens when input samples are 'skipped' during the filtering, as shown in Figure 18. Figure 17 shows that, for the higher speeds, the response is periodic due to this effect. Therefore, we change the response of the 1D filter, to actually suppress the very highest frequencies for high speeds, instead of increasing the amplification (as in Figure 10). This can be achieved by using an interpolation method that suppresses these frequencies before the tap multiplications, i.e. that uses (averages) more original samples to compute an interpolated sample. Figure 19a illustrates this. An alternative is to first interpolate more samples, and use a filter with more taps that suppresses the high frequencies. Figure 19b, where the number of taps has been increased from 3 to 5, illustrates this. The suppression of high frequencies at high speeds can be achieved by cascading with a speed-dependent low-pass filter, or by storing a number of (1D) filters for various speeds. The resulting filter for different speeds is shown in Figure 20. Figure 21 shows the response as a function of speed and spatial frequency, and the result of the filter combination with display+eye.

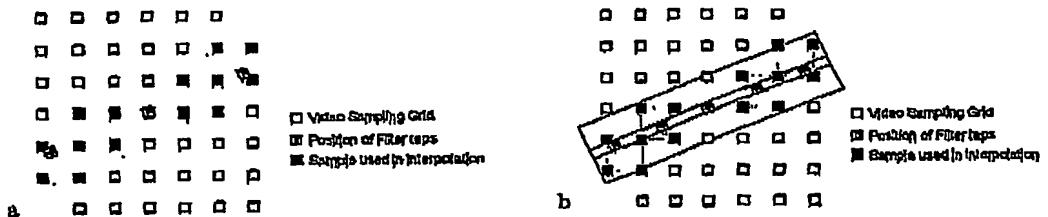


Figure 19. Samples used to interpolate the rotated filter

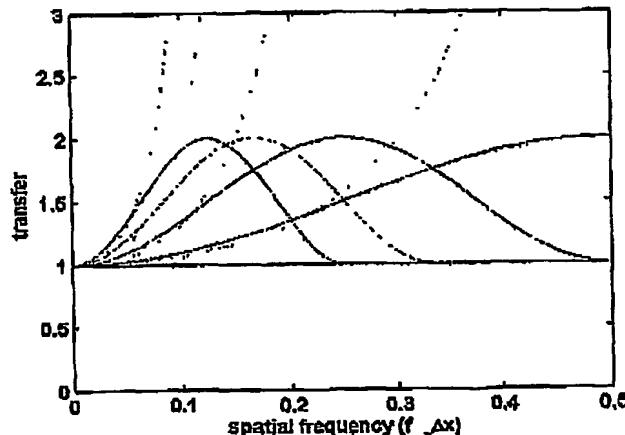


Figure 20. Response of filter with varying tap-distance and high-frequency suppression, and the corresponding 'ideal' inverse filter for different speeds.

Furthermore, a low-pass filtering perpendicular to the motion direction can also be beneficial (to suppress noise), which can be achieved by also using samples further away from the line of the motion in the interpolation, as indicated in Figure 22. The resulting filter has a low-pass behavior perpendicular to the motion, and a band-pass behavior (combination of low-pass interpolation and high-pass 1D filtering) along the motion.

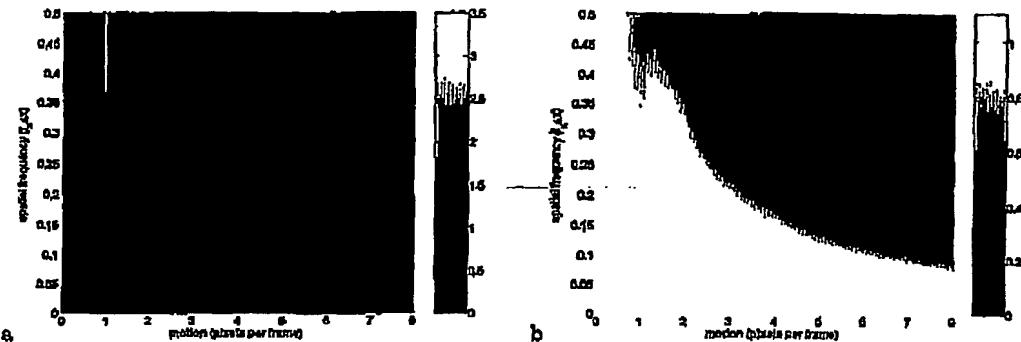


Figure 21. Speed dependent MCIF. a) filter response as a function of speed, b) Combined response of filter and display+eye.

Finally, alternative to implementing the filters as a directional dependent interpolation followed by a (1D) filtering, the filters can be calculated for a number of angles and speeds (a number of motion vectors), and stored in a table. The filtering then comes down to applying a different 2D filter for each pixel, where the coefficients of this filter are according to the principles mentioned in this section. The number of stored filters can be limited, when 'intermediate' filters are calculated (interpolated) based on the stored ones.

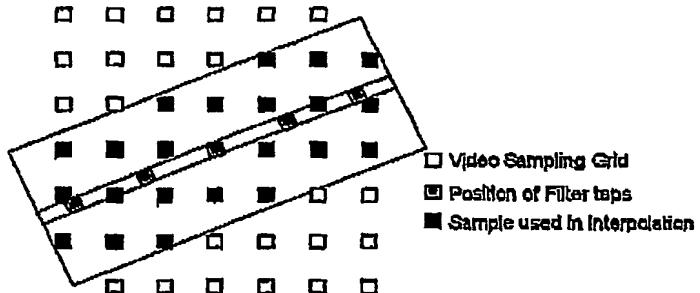


Figure 22. Samples used to interpolate the rotated filter, taking also samples perpendicular to the motion vector

## 5. RESULTS

We have tested the MCIF system of Figures 15 and 21 on an LCD-TV simulation setup, which consists of a PC-based video streamer that can play back stored sequences in real time, a DVI to LVDS panel interface board, and a 30 inch LCD-TV panel (1280x768@60Hz, without additional processing). Although the panel had a listed response time of 12 ms, we performed a measurement of the response times for each gray level transition, and found an average response time of 20ms. To further increase the response speed, (a moderate amount of) overdrive was used to get the response time to within one frame time.

By means of comparison with a CRT display, we could observe that there was not visibly more motion blur on the LCD than on the CRT. Only for very critical (graphics-like) sequences, motion blur was still visible. In order to visualize the results in this paper, we simulated the blur that is seen by an eye tracking viewer. This simulation is based on motion vectors that are obtained from the motion estimator from Section 3. The

light intensities as a function of time, resulting from the temporal response of the display, are integrated along the motion trajectory. Figure 23 shows an example of the perceived image on the display, for an impulse-type display (the "original" image), a hold-type display and a hold-type display with MCIF correction. This example illustrates that the MCIF method can reduce motion blur, due to the sample-and-hold effect, to a large extent.

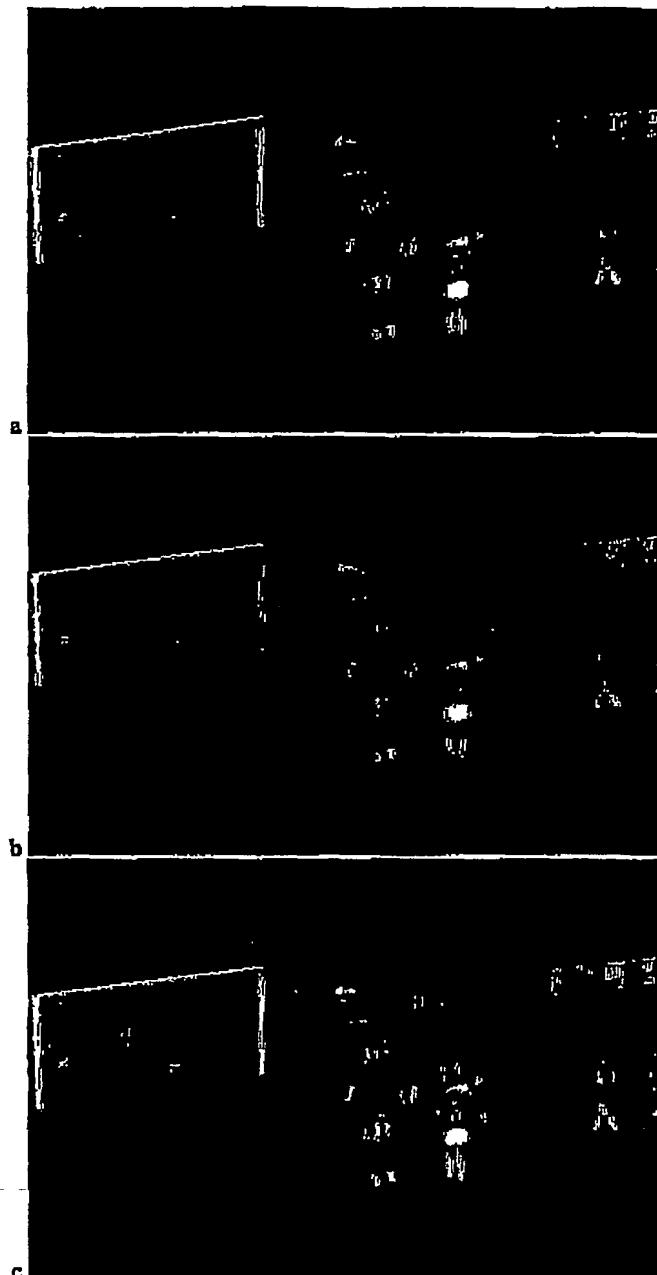


Figure 23: Results of motion compensated inverse filtering. a) original image; the scene pans from left to right. b) (simulated) motion blur on a sample-and-hold LCD display, as seen by an eye tracking viewer. c) (simulated) image as seen by an eye tracking viewer, after pre-correction with MCIF.

## 6. Conclusions

Even the fastest responding LCD panels suffer from motion blur due the sample-and-hold behavior. Motion compensated inverse filtering is able to reduce motion blur for common video material. It is an alternative to motion blur reduction methods that change the panel operation. This paper presented the implementation of an efficient MCIF method, and further showed methods to prevent noise amplification and other gain limitations.

## 7. Applications of the invention

The invention described above can be used for various types of non-stroboscopic displays. Some of those are briefly described below. Non-stroboscopic non-emissive displays, such as Liquid Crystal Displays (LCD), Plasma Panel Displays (PDP), Thin Film Transistor (TFT) displays, Liquid Crystal on Silicon (LCOS) displays or Colour Sequential Displays, consist of a display panel having a row and column array of picture elements (pixels) for modulating light, means for illuminating the display panel from the front or back side, and drive means for driving the pixels in accordance with an applied input video signal. Quite similar, non-stroboscopic emissive displays, such as Organic Light Emitting Diodes (O-LED) displays or Polymer Light Emitting Diodes (Poly-LED) displays, consist of a display panel having a row and column array of pixels (LEDs) and drive means for driving the pixels (LEDs) in accordance with an applied input video signal. However, the pixels (LEDs) emit and modulate light by themselves without requiring illumination from the front or back side.

A display according to the invention can be used in various types of devices. Examples of such devices are a television and a monitor. But other applications for such a displays are also possible, for example a mobile phone, instruments, and head-mounted displays.

The invention can be realised as a separate unit processing the video signals prior to sending them to a display. Such a unit can be made as a chip, potentially including other functions. Furthermore, the unit may be realised by a programmable devices, loaded with a program executing the various processing steps.

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## CLAIMS:

1. Method for reducing motion blur due to a motion-dependent low-pass filtering on non-impulse type displays, characterized in that,
  - The motion of moving components in the input video signal is estimated
  - Coefficients of a high-frequency boosting filter are calculated, based on this motion vector
  - At increasing speed, high frequency components are less boosted than the medium frequency components.
  - The input video signal is filtered using this high frequency boosting filter
  - The output video signal is generated by combining the input and filtered signal.
2. Method as in claim 1, further characterized in that, samples along a line determined by the motion vector are first interpolated, and the high-frequency boosting filter is applied to these interpolated samples.
3. Method as in claim 2, further characterized in that, interpolation of samples along the motion trajectory includes an extra low-pass (averaging) filter to suppress the highest frequencies for high speeds, such that only medium frequency components are boosted by the high frequency boosting filter.
4. Method as in claim 2, further characterized in that, for high speeds, the high frequency boosting filter is combined with a low-pass filter, such that only medium frequency components are boosted.
5. Method as in claim 1, further characterized in that, a low-pass filtering perpendicular to the motion direction is included.
6. Method as in claim 5, further characterized in that, the low-pass filtering perpendicular to the motion direction is performed during the direction dependent interpolation, by also using samples further away from the line describing the motion vector.
7. Method as in claim 1, further characterized in that, the direction and speed dependent high (medium) frequency boosting filters are stored for a number of motion vectors, and these stored filters are used to update the (2D) applied filter for each pixel, interpolating between stored filters if needed.

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